HIGH FREQUENCY COMMUNICATION SYSTEMS

Lecture 10

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- mmWave Communications
  - mmWave Antennas
- mmWave Beamforming Algorithms

MMWAVE COMMUNICATIONS

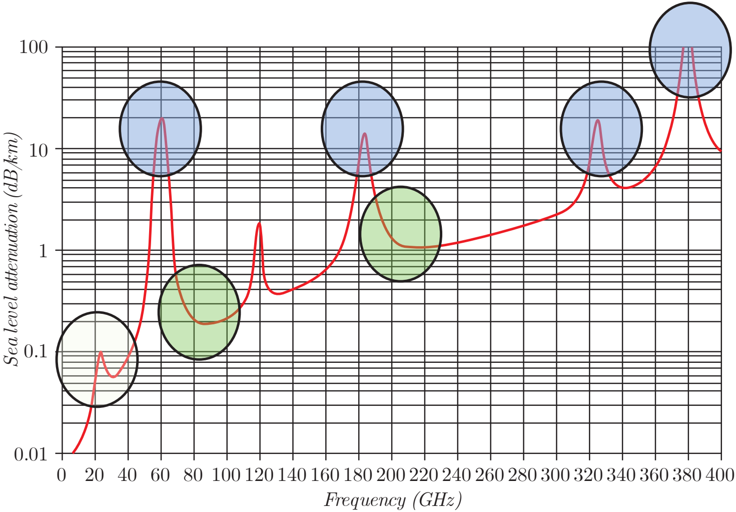
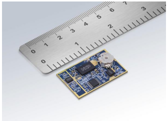


Figure 1: EM wave attenuation due to O_2 molecules in air in the mmWave spectrum. [T. S. Rappaport *et al*, Proceedings of the IEEE, vol. 99, no. 8, pp. 1390-1436, 2011.]

- λ at mmWave becomes so small that the O_2 and H_2O molecules in air severely affect the wave propagation
- Besides this, we have the effects of weather such as rain, fog etc.
  - The wave is also attenuated due to distance and other obstacles
- We require directional antennas for effective communications.

- mmWave signals have extremely short wavelengths ($\lambda = 10.70$ mm at 28 GHz, $\lambda = 5$ mm at 60 GHz)
- As a result, objects that would scatter EM waves may now act as *reflectors*.
  - Significantly higher multipath effects at mmWave as compared to microwave systems
- These small dimensions enable extremely integrated and physically small antennas
  - In-package and on-chip antennas
  - We can make the antennas with the same fabrication process as the rest of the IC



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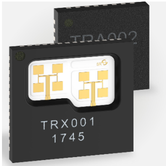


(b)

Figure 2: An on-chip 3 GHz to 5 GHz and a 120 GHz antenna in package (8 mm by 8 mm) (©NXP Semiconductors, Silicon Radar).

- The wave propagation can be modelled macroscopically *large-scale channel effects* or microscopically (*small-scale channel effects*)
- Lets start with the *Friis* transmission equation:

$$P_{\mathrm{Rx}} = \frac{P_{\mathrm{Tx}} \mathrm{Gain}_{\mathrm{Tx}} \mathrm{Gain}_{\mathrm{Rx}}}{\text{Loss Factor}} \left(\frac{\lambda}{4\pi D} \right)^2$$

	$f_c = 460$ MHz	$f_c = 2.4$ GHz	$f_c = 5$ GHz	$f_c = 60$ GHz
$d = 1$ m	-25.7 dB	-40 dB	-46.4 dB	-68 dB
$d = 10$ m	-45.7 dB	-60 dB	-66.4 dB	-88 dB
$d = 100$ m	-65.7 dB	-80 dB	-86.4 dB	-108 dB
$d = 1{,}000$ m	-85.7 dB	-100 dB	-106.4 dB	-128 dB

Figure 3: Freespace Path Loss at different frequencies.

From previous lectures, the antenna gain is:

$$\mathrm{Gain}_{\max} = e_{\max} A_{\max} \frac{4\pi}{\lambda^2}$$

We typically treat $A_{\max} \propto D^2$. For a uniform linear array of N elements,

$$D_{\text{array}} = N \times D_{\text{element}}$$

For a two-dimensional array, the gain therefore, becomes even higher,

$$\mathrm{Gain}_{\max} \propto \frac{4\pi D_{\text{array}}^2}{\lambda^2}$$

$$\boxed{P_{\text{Rx}} = \frac{P_{\text{Tx}} e_{\text{Tx}} e_{\text{Rx}} \left(D_{\text{Rx}} D_{\text{Tx}}\right)^2}{L(\lambda d)^2}}$$

- As frequency increases, we can stack more antenna elements in an array within a given size
  - Results in increased gain
- The Tx and Rx antennas become highly directional
  - The steering of the beams becomes an altogether new topic of research
  - The path loss can be overcome
- For a given gain, the effective area is proportional to $1/f^2$
- However, the antenna efficiency typically decreases as we go up in frequency

According to the famous *Shannon* capacity theorem, a wireless channel capacity, C for a signal with power P is,

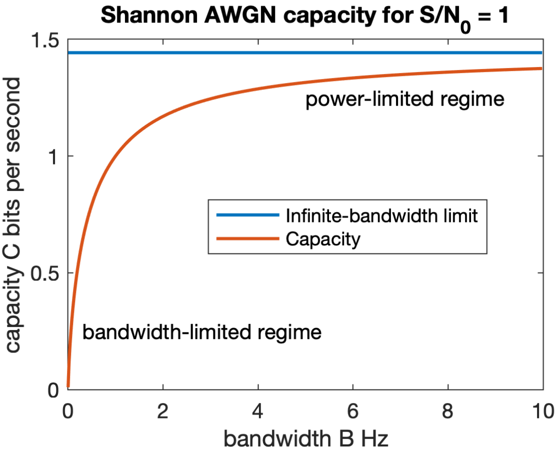
$$C = \mathrm{BW} \log_2 \left(1 + \frac{P}{\mathrm{BW}\, N_0}\right)$$

where, BW is the signal bandwidth, and N_0 is the noise spectral density.

- For a given power P_0, the capacity is an increasing function of BW.
- However, we approach a limit,

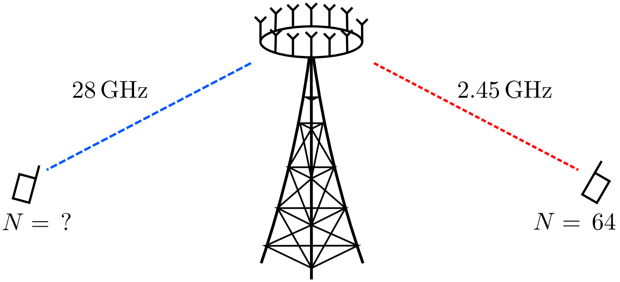
$$\lim_{\mathrm{BW} \to \infty} \mathrm{BW} \log_2 \left(1 + \frac{P}{\mathrm{BW}\, N_0}\right) = \frac{P}{\log(2) N_0}$$

We can only ever so get some bandwidth benefits out of a mmWave system.



Consider, we want to have the same quality of service (i.e. same link budget) in the scenario below. What is the approximate number of antenna elements required in the mmWave case?

Treat the antennas as ideal with same distance from the transmitter and similar efficiencies.



From the *Friis* formula, we can estimate the link budget. We would like to have the same power received in both the cases.

An approximate value, discounting the efficiencies, interference and noise can be written as:

$$N_2 \approx \left(\frac{f_2}{f_1}\right)^2 N_1$$

$$N_2 \approx 136.11 \times 64$$

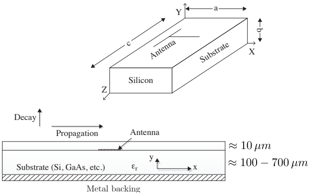
We need ≈ 136 times more antennas to maintain the link budget!

MMWAVE ANTENNAS

- So far, we have considered an ideal scenario where we ignored all the factors that affect antenna performance
  - In reality, mmWave antennas are in-efficient
  - Feeding networks become complex due to large number of array elements
- With good designs, we can achieve antenna efficiency up to 80 %
- Mainly there are two types of designs, *on-chip* and *in-package* antennas

- The biggest motivation behind the use of on-chip antennas is the low-cost and integration with the rest of electronics
- We can achieve gain up to 30 dB and antenna efficiency over 85 %
- There are four design challenges that one has to consider
    - Generation of surface waves
    - Direction of antenna radiation
    - Substrate loss
    - Resonant frequency of the substrate
- As the antenna may be surrounded by nearby metal vias, we need to consider coupling effects.

- The nature of the structure supports the unwanted generation and radiation of surface waves
- Surface waves travel along the axis of the substrate
  - They reduce the efficiency
  - Increase the coupling between adjacent structures
- As a remedy, we can increase the substrate thickness to suppress the surface waves
  - However, this has detrimental consequences on antenna efficiency



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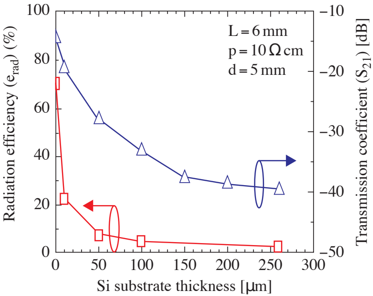
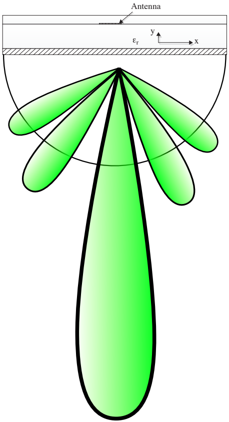
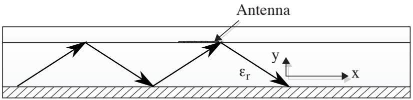


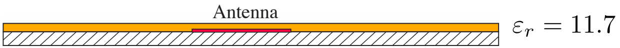
- Due to the high dielectic permittivity of Si ($\varepsilon = 11.7$), the direction of radiation is into the substrate rather than out.
- Moreover, the waves get attenuated in the substrate before they can leave the structure
- Hemispherical dielectric lenses are used to *focus* the waves before they radiate from the structure.



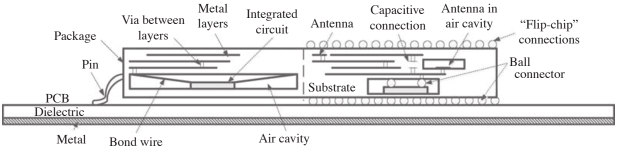
- The presence of metal vias
- Lower permittivity substrates should be used to avoid the generation of surface waves.
- Most of the waves actually get trapped and therefore attenuated to the low critical angle of Si $(\arcsin 1/\sqrt{\varepsilon_{r,sub}})$



Alice is an antenna designer and needs to decide the best material as well as the topology of the antenna that will be *integrated* with a CMOS circuit. The current design is giving her a poor radiation efficiency of 30 %. Suggest some improvements to increase the antenna performance.

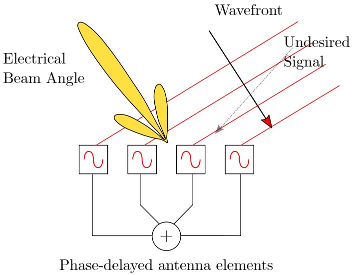


- An in-package antenna consists of several co-planar metal layers
- It is manufactured using a packaging process
- Connections within the layers are made through vias
- Due to better isolation, we can get better antenna performance compared to on-chip antennas
- Antenna is created through an air cavity
- Design requires a careful selection of permittivity of the substrate
- Scaled microwave designs are used to fabricate antennas



BEAMFORMING ALGORITHMS

- For beamforming, determining the direction of an incoming signal through the direction of arrival (DoA) algorithms is a key element.
- The goal is to develop a machine like the human ear
- DoA or direction finding algorithms *reconstruct* the signals from each direction and try to determine the identity of the signal source.



$$S_i = \sum_{\ell=1}^{N} m_\ell(t) e^{-j\overrightarrow{k_\ell}\cdot(\overrightarrow{r_i}-\overrightarrow{r_1})}$$

here $\overrightarrow{k_\ell}$ is the wave-vector, $\overrightarrow{r_1}$ and $\overrightarrow{r_i}$ are the positions of the reference and i-th array elements.

We seek to construct a matrix, $\mathbf{X}$ for an array of M elements with N snapshots recorded in time.

$$\mathbf{X} = \begin{bmatrix} S_1(t_1) & \dots & S_1(t_N) \\ \dots & \dots & \dots \\ S_M(t_1) & \dots & S_M(t_N) \end{bmatrix}$$

Next, a covariance matrix $\mathbf{R}$ needs to be estimated for the incoming signal $\mathbf{X}$ polluted with noise N,

$$\mathbf{R} = \left(\frac{1}{N}\right) \mathbf{X}^* \mathbf{X}$$

We also need to *track* the directions in which the array is activated. We represent this with a steering vector,

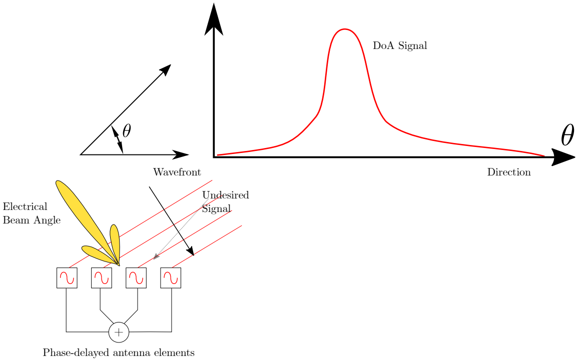
$$\mathbf{a}_{\text{direction}} = \begin{bmatrix} 1 & e^{-j\overrightarrow{k_l}\cdot(\overrightarrow{r_1}-\overrightarrow{r_2})} & \dots & e^{-j\overrightarrow{k_l}\cdot(\overrightarrow{r_1}-r\vec{M})} \end{bmatrix}$$

The next step involves the intensive computation of weights which will be applied to each direction vector:

$$\mathbf{w} = \frac{\mathbf{R}^{-1}\mathbf{a}_{\text{direction}}}{\left(\mathbf{a}^{*}_{\text{direction}}\,\mathbf{R}^{-1}\mathbf{a}_{\text{direction}}\right)}$$

- There are established ways to solve the above matrices
- Two of the most famous direction finding algorithms are multiple signal classification (MUSIC) and estimation of signal parameters via rotational invariance techniques (ESPIRIT)
- Using some terminologies from Linear Algebra, both the algorithms above assume the covariance matrix column space is spanned by two orthogonal subspaces
  - They are signal and noise subspaces

DOA OUTPUT



θ
DoA Signal
θ
Wavefront
Direction
Electrical
Beam Angle
Undesired
Signal
Phase-delayed antenna elements

Chapter 4

T. S. Rappaport, R. W. Heath, R. C. Daniels, and J. N. Murdock, Millimeter wave wireless communications. Upper Saddle River, NJ: Prentice Hall, 2015.